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Investigation of Exhaust Valve Failure in Heavy - duty Diesel Engine

Nurten VARDAR[1♠], Ahmet EKERİM[2]

[1]Yildiz Technical University, Faculty of Mechanical Engineering, 34349 Istanbul, Turkey
[2]Yildiz Technical University, Faculty of Chemical and Metallurgical Engineering, 34220 Istanbul, Turkey

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ABSTRACT

The exhaust valves of a diesel engine are exposed to thermal and mechanical overstress which may be sources of valve failures. The exhaust valves usually fail as a result of different failure modes such as wearing, fatigue and corrosion. In order to describe these modes a failed exhaust valve which was belonged to a heavy-duty diesel engine is investigated. The investigation of the failure was carried out by using several experimental tests including optical emission spectroscopy, optical microscopy, scanning electron microscopy SEM and EDX. It was found that the carbon content of the material of the failed valve decreased. Angular titanium phases were found in microstructure of the material of the failed valve. Fuel-born vanadium and chromium carbide were detected on the surface of the valve. It was concluded that the valve was broken down before its expected service life.

Key Words: *Failure; exhaust; valve; diesel; corrosion.*

1. INTRODUCTION

Either exhaust or intake valve are very important components of a diesel engine and control the flow of gases in and out of engine cylinders. Air flows into the cylinder when the intake valves are open. Combustion process takes places in the cylinder after the intake valves close. The exhaust valves open when the combustion process ends and burned gases flow out of the cylinder.

The exhaust and intake valves are exposed to thermal and mechanical overstress which can be sources of valve failures. During the valve closing, a combination of impact and sliding can lead to valve seat wear. Impact on a valve closure causes plastic deformation of the seating face surface and the formation of a series of circumferential ridges and valleys. It also leads to surface cracking and subsequent material loss from seat inserts at high closing velocities [1-4]. Valve spindle seating pressures should be in the range of 500-550 bars to give good sealing, while seating velocity should be between 0.15-0.2 m/s to be consistent with low wear and good valve dynamics [5].

The exhaust valves are exposed to thermal overstress more than the intake valves because the incoming air cools the intake valves. Exhaust valves have surfaces which are affected by the high temperature combustion

♠Corresponding author, e-mail: vardar@yildiz.edu.tr

flame and the high temperature of combustion gases flowing past the exhaust port during the exhaust process. For this reason exhaust valves are much more vulnerable to erosion and burning than intake valves. If the valves do not receive adequate cooling, they can overheat, burn and fail. Anything that interferes with valve cooling or creates extra heat in the valve can lead to premature valve failure. A build-up of deposits on the valve face and seat can have an insulating effect that slows cooling and makes the valve run hot. If deposits build-up in one spot or flake off in another, it can allow leaks that create hot spots on the valve and result in channelling (grooves eroded or burned into valve). The deposits formed on an exhaust valve are from the reaction of fuel-borne contaminants and lubricating oil during combustion as well as the reaction of combustion products with valve materials [6-8]. The sulphur, vanadium and sodium content in the fuel oxidize during the combustion process to form sulphur dioxide, sulphur trioxide, sodium oxide and vanadium pentoxide. These oxides react with each other and the calcium content in the lubricating oil to form low-melting point salts. Particles of these salts deposit themselves on the valve surfaces in their molten state and get cooled sufficiently to adhere to valve spindle, preventing them from being carried away by the exhaust gases. At temperatures of 550 ^{o}C and upwards, the deposited salts change into their molten state as respective melting points are reached. In a molten state these salts flow along the grain boundaries and, depending on the valve material, dissolve the protective oxides on the grain boundaries, thereby exposing the less resistant grain to these corrosive salts. This is called inter-granular corrosion and is the mechanism that leads to burn away on valve face [5, 9].

The valve breakage is an important type of valve failures. The valves usually break due to a failure mode called fatigue. The valves are repeatedly loaded and unloaded when they open and close, they can tire and fatigue if the environmental conditions are too severe. The mean by the conditions are combination of temperature, stress and corrosive environment. If any of these conditions is excessive, the valve will break its weakest point. The valves can also break by impact. An impact break is usually a secondary fracture that takes place because the valve may drop down into the cylinder of a running engine and is hit by the piston which causes it to break [10].

In order to investigate the effect of failure modes on damaged valves, a failed valve taken from a power plant was examined. This paper describes a detailed metallurgical investigation and fractographic analysis on that particular exhaust valve of a diesel engine, which catastrophically failed in service. The failure had taken place at the plates of the exhaust valve.

2. VISUAL INSPECTION

The macro cracks on the seating area of the damaged valve are shown in Figure 1. As can be seen from the figure the macro cracks have been formed after the micro cracks get to a critical length through the impact area of the valve which is illustrated in Figure 2. These cracks are attributed to the mechanical stress resulting from the closing of the valve. Figure 3 shows a different view of the valve. It was reported that the valve had catastrophically failed and parts of the table had dropped down in to the cylinder.

Figure 1. Cracks on table of failed exhaust valve.

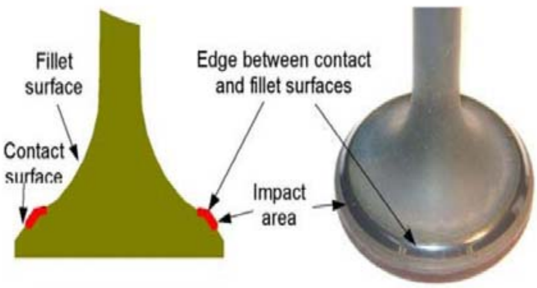

Figure 2. Location of impact area on the exhaust valve.

Figure 3. Catastrophic failure on the valve table.

3. EXPERIMENTAL PROCEDURE

The investigation of the failure was carried out by using several experimental tests including optical emission spectroscopy, optical microscopy with Leica DFC280 image analyser, and scanning electron microscopy (SEM). EDX analyse unit was used in order to describe the phases and X-Ray fluorescence (XRF) was used to analyse the failed surface. Specimens were taken from stem and table of the failed valve. The metallographic samples were prepared by standard techniques and were etched with aqua regia for 30 seconds.

4. RESULTS AND DISCUSSION

4.1. Chemical composition examination

From the results of the composition examination of the valve material the composition of the base alloys was found to be X45CrSi93 which is a ferritic-martensitic, force shaped and annealed valve steel [11]. As can be seen from Table 1 the chemical compositions of valve stem and table material are similar and the valve is monometallic. The carbon contents were found to be 0.28-0.34 % in material of the failed valve. These values are smaller than 0.40-0.45 % which is the standard values of carbon contents of the X45CrSi93. The causes of considerable decrease of the carbon content in valve material likely owing to decarburisation which was occurred in whole structure. The decarburisation arises at high temperature values and decreases the strength of the material.

Table 1.Chemical compositions of valve stem and plate material-instrumental analyse results.

N	Fe	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Co	Cu	Sn	Ti	V	W
1	86.	0.3	2.9	0.5	0.01	0.01	8.8	0.04	0.31	0.03	0.01	0.1	0.01	0.02	0.01	0.05
2	87.	0.2	2.5	0.4	0.01	0.01	8.5	0.05	0.30	0.01	0.01	0.1	0.01	0.03	0.01	0.05

4.2. Fractography

The SEM image taken from fracture surface is shown in Fig. 4. Fatigue striations and beach marks on the fracture surfaces do not appear. Fatigue striations and beach marks indicate that the fracture was produced by the propagation of fatigue cracks [12]. Then, it may be concluded that the fatigue was not a possible cause of failure in the valve and the valve was broken down before its expected service life.

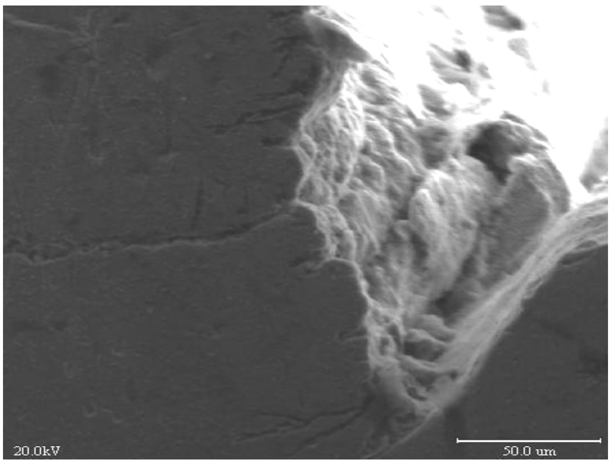

Figure 4. SEM image of the fracture surfaces of the failed valve.

4.3. Metallurgical Investigation

As can be seen from Figure 5 the soft annealed matrix of the valve material still presents although the material structure had decomposed with high temperature values. The microstructure consists of carbide particles precipitated in grain boundaries.

The presence of angular phases in stem and table of the failed valve was observed. The angular phases present in both stem and table of the failed valve are shown in Figure 6 and Figure 7 respectively. The angular phases, most of which have fairly smooth square shapes, were also observed by scanning electron microscopy. Figure 8 shows an SEM image of an angular phase. Figure 9 shows the results of the EDX analysis, which was performed in order to analyse the angular phase seen in Figure 8.

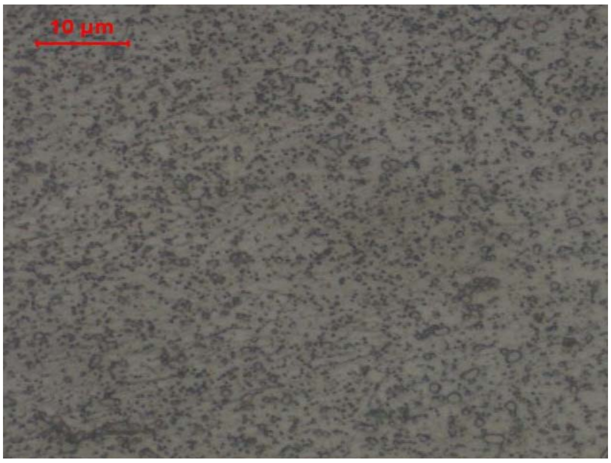

Figure 5. Microstructure of matrix.

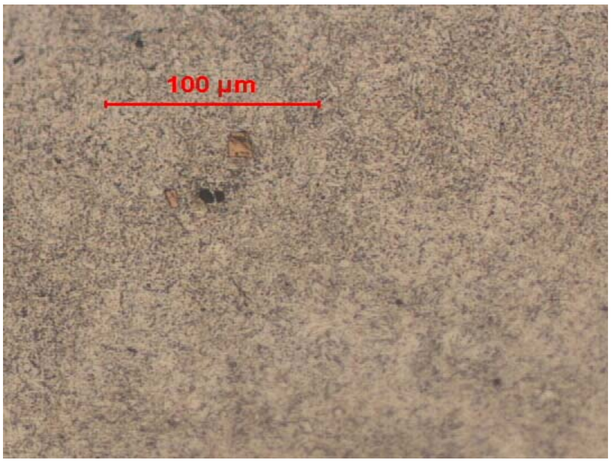

Figure 6. Microstructure of valve stem.

Figure 7. Microstructure of valve table.

According to the results of the EDX analyse the angular phases are titanium, which may be due to not maintaining an adequate alloying temperature value during addition of titanium and therefore causing titanium not to dissolve in material structure. The angular phases had caused crack initiation in the material structure as shown in Figure 10.

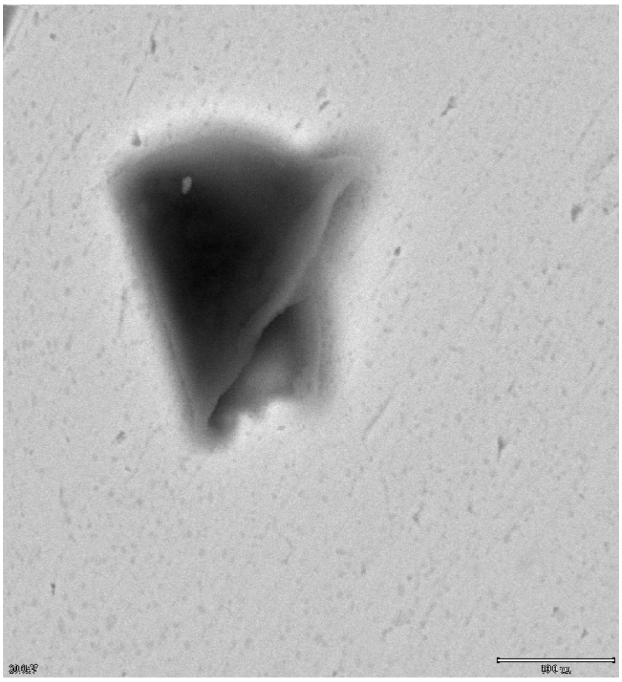

Figure 8. SEM image of angular phase.

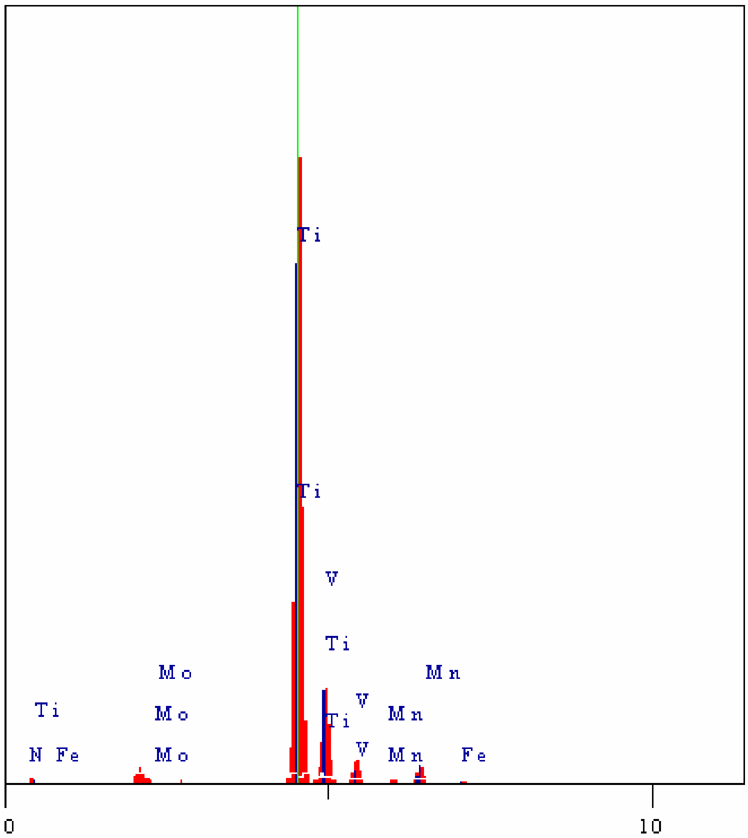

Figure 9. EDS analyse results of the point shown in Figure 8.

Figure. 10. Image of crack initiation in valve table.

4.4. XRF Results

As can be seen from the Figure 11 chromium carbide and vanadium were detected on the surfaces of the failed valve. The presence of the chromium carbide is almost unavoidable in high ambient temperature. The presence of the vanadium indicates the existence of the fuel-borne vanadate compounds which are causes of the hot corrosion on the surfaces of the valve [5].

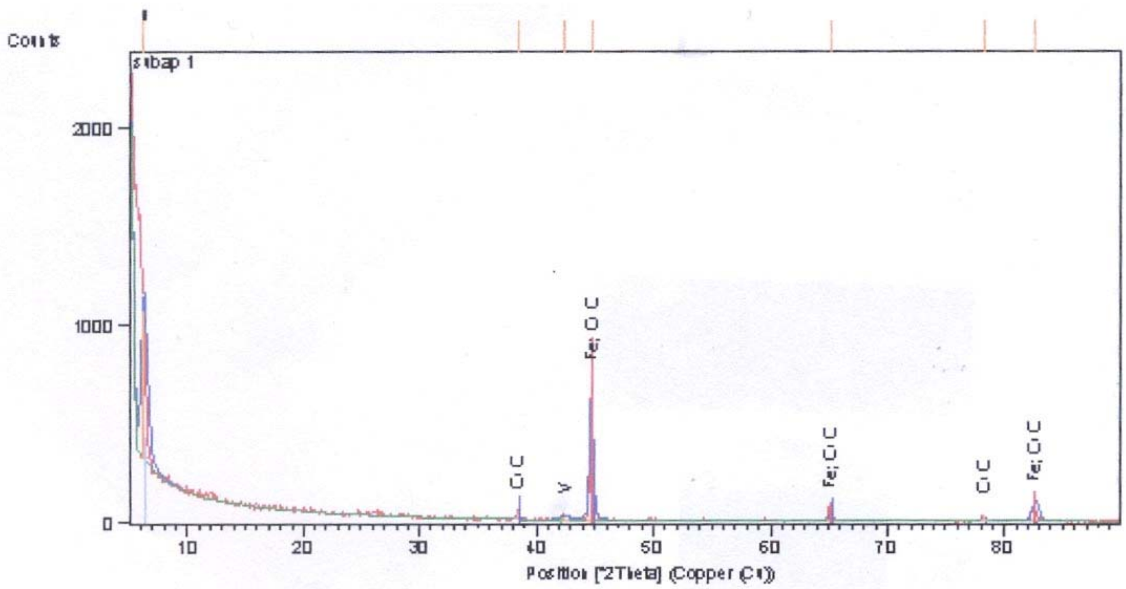

Figure 11. XRF analyse results.

5. CONCLUSION

The different failure modes affecting the valve failure are discussed. The combination of impact and sliding during the valve closing can lead to valve seat wear. The deposits formed on an exhaust valve are due to the reaction of fuel-borne contaminants and lubricating oil during combustion as well as the reaction of combustion products with valve materials. The build-up of deposits on the valve face and seat can have an insulating effect that slows cooling and makes the valve run hot and therefore valves can lead to hot corrosion. Another failure mode of valves is fatigue, which may cause the valve to break. Valves usually fail as a result of different failure modes like fatigue, corrosion, wearing and impact which are explained above. The reason for a valve failure may be one of the above explained failure modes or some sort of combination of them. In order to see that combination a failed exhaust valve is examined. It is possible to bring forward following conclusions from the theories well-known and failure modes discussed above. The fractures on the failed valve were observed around the impact area at the table of the failed exhaust valve. Impact area of the valve is exposed to maximum mechanical forces and stresses. These mechanical stresses cause valves to become weaker. The material of the failed exhaust valve is X45CrSi93. There was a dramatic decrease in the carbon content of the material of the failed valve. It was found between 0.28 and 0.34% although the normal value of carbon content is 0.40-0.45%. The causes of considerable decrease of the carbon content in valve material likely owing to decarburisation which was occurred in whole structure. Angular titanium phases were found in microstructure of the material of the failed valve. The angular phases had caused crack initiation in the material structure. Vanadium was found on the surfaces of the failed valve. The fuel-born vanadium has caused the corrosion on the valve. Chromium carbide was detected on the surface, which is due to high ambient temperature.

Since fatigue striations and beach marks did not appear on the fracture surfaces, the fatigue was not a possible cause of failure in the valve and the valve was broken down before its expected service life.

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